Vortex Coupling in Propulsive Pulsed Jets

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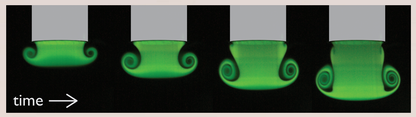
Motivation

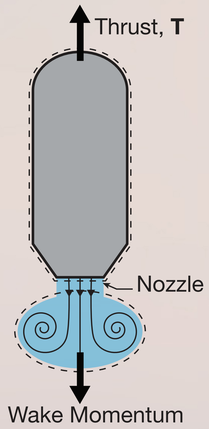
For underwater vehicles that need to perform **precise** maneuvers, **pulsed jets** deliver impulse with fine control that can't be matched by propellers.[1]

However, for arbitrary motion, vehicles require multiple thrusters that could interact with each other depending on the design.

When jets act simultaneously, how will **hydrodynamic coupling** between nearby jets **affect thrust production**?

Background





1. Unlike continuous jets, a pulsed jet **initially forms a vortex ring** at the nozzle tip.[1-3]
2. Vortex formation introduces a **nozzle overpressure** while the jet is developing.[3]
3. Overpressure relates the thrust to the vortex ring dynamics according to:

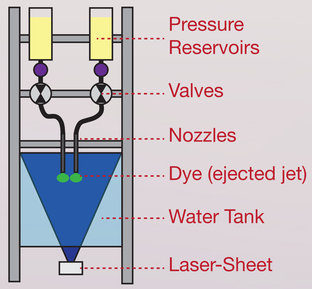
$$T = A_n(\rho u_j^2 + p_n) \approx 2\rho u_{cm}\dot{V}_{cv} + \int_{S_{vb}} p_{vb}\,\hat{n}\cdot\hat{z}\;dA$$

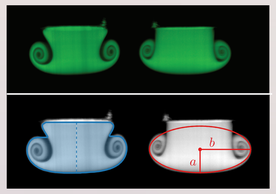
jet inertia; overpressure; vortex ring growth; pressure around vortex ring

Experiment ($Re \approx 350$)

To test the jet interactions, we ejected two jets with variable spacing.

Vortex rings were recorded at high speed using fluorescent dye and a laser.



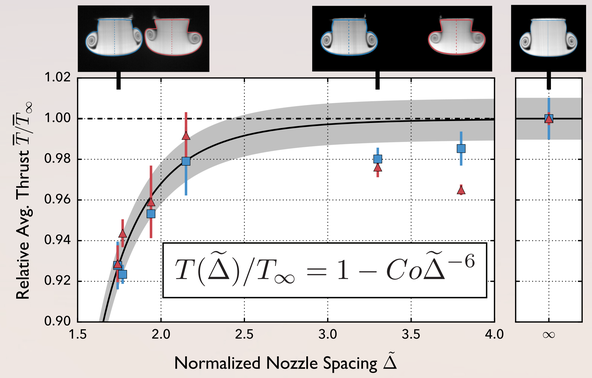


By measuring the **shape**, **size**, and **motion** of the wake, we can estimate **thrust** from the videos.[2]

Results

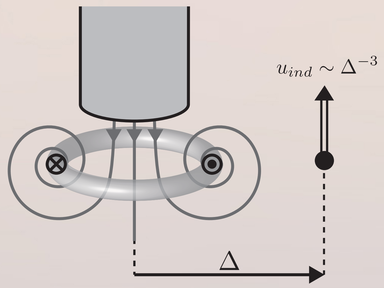
When two jets are pulsed simultaneously, **less thrust** is produced **as the jets get closer.**

The thrust drop depends on nozzle spacing, nozzle diameter, and a dimensionless coupling coefficient, $Co = 2.04$



Our Interaction Model

What's the physics behind the observed behavior?



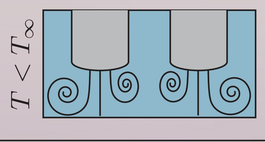
By considering that the jets will interact during formation through **vortex induction**, we predict that the thrust should change according to:

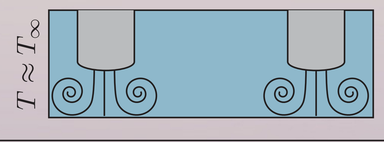
$$T \sim \rho u_{ind}^2 \sim \tilde{\Delta}^{-6}$$

To understand why the thrust drops as the nozzles get closer, consider how the **streamlines** behave.

When the jets are closer, the symmetry requires that the nozzle **streamlines straighten**, **decreasing the overpressure**.

Since the jet velocity is constant, **less thrust is produced**.





Conclusions

1. For nearby pulsed jets, **vortex interactions** between the jets force the streamlines to straighten, and thus **generate less thrust**.
2. This **effect is highly localized**, scaling as $\tilde{\Delta}^{-6}$!
3. Our model suggests that careful **control of jet timing** could **enhance thrust production**, similar to how jellyfish exploit stopping vortices for efficient propulsion.
4. These results can be generalized to more nozzles for first order performance estimates.

More details can be found in our paper:

Effects of multijet coupling on propulsive performance in underwater pulsed jets. Phys. Rev. Fluids, 1, 034501. (2016)

For a different view of this project, check out my **YouTube** video with Nicole from **FYFD**!

References

(1) Mohseni, K. Pulsatile vortex generators for low-speed maneuvering of small underwater vehicles. *Ocean Engineering*, **33**, 2209 (2006).
(2) Ruiz, L. A., Whittlesey, R. W. & Dabiri, J. O. Vortex-enhanced propulsion. *Journal of Fluid Mechanics* **668**, 5-32 (2010).
(3) Krueger, P. S. & Gharib, M. The significance of vortex ring formation to the impulse and thrust of a starting jet. *Physics of Fluids* **15**, 1271 (2003).

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